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# Maize Water Use in Living Mulch Systems with Stover Removal

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**Abstract**

Constraints to maize (*Zea mays* L.) stover biomass harvest may be mitigated by using a living mulch (LM) to offset C exports and control soil erosion. Living mulches can compete with the main crop for resources, particularly water. The objectives of this research were to quantify soil water dynamics and maize water use in continuous maize with stover removal. Continuous soil water content (SWC) and reproductive whole-plant water use were measured in no-till maize growing in LMs of creeping red fescue (CF) (*Festuca rubra* L.), Kentucky bluegrass (KB) (*Poa pratensis* L.), and a no-LM control between 2008 and 2010 near Ames, IA. In 2 yr with excessive rainfall (2008 and 2010), LMs increased SWC compared to the control at 15 cm. No-till LM treatments lowered grain yield in 2008 and 2010 compared to the control, although a KB fall strip-till treatment, which was part of the larger research study, produced yields that were not different than the control all 3 yr. Reproductive water use efficiency for no-till KB in 2008 and 2009 (51 and 42 g grain per cm water) was 21 and 14% greater than the control (42 and 37) but 24% lower in 2010 (41 vs. 51). Maize water use in the control exhibited a bimodal response averaged across the 3 yr with peak water use occurring at the R1 through R2 period (0.58 cm $d^{-1}$) and declining to 0.26 cm $d^{-1}$ during R5 through R6. In contrast, no-till KB exhibited a simple negative linear relationship with water use rates declining from a high of 0.47 cm $d^{-1}$ during the R1 through R2 period to 0.22 cm $d^{-1}$ during R5 through R6. These results indicate LMs may increase SWC and utilize water more effectively, particularly when combining strip-till and herbicide management.

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RESEARCH

# Maize Water Use in Living Mulch Systems with Stover Removal

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## ABSTRACT

Constraints to maize (*Zea mays* L.) stover biomass harvest may be mitigated by using a living mulch (LM) to offset C exports and control soil erosion. Living mulches can compete with the main crop for resources, particularly water. The objectives of this research were to quantify soil water dynamics and maize water use in continuous maize with stover removal. Continuous soil water content (SWC) and reproductive whole-plant water use were measured in no-till maize growing in LMs of creeping red fescue (CF) (*Festuca rubra* L.), Kentucky bluegrass (KB) (*Poa pratensis* L.), and a no-LM control between 2008 and 2010 near Ames, IA. In 2 yr with excessive rainfall (2008 and 2010), LMs increased SWC compared to the control at 15 cm. No-till LM treatments lowered grain yield in 2008 and 2010 compared to the control, although a KB fall strip-till treatment, which was part of the larger research study, produced yields that were not different than the control all 3 yr. Reproductive water use efficiency for no-till KB in 2008 and 2009 (51 and 42 g grain per cm water) was 21 and 14% greater than the control (42 and 37) but 24% lower in 2010 (41 vs. 51). Maize water use in the control exhibited a bimodal response averaged across the 3 yr with peak water use occurring at the R1 through R2 period (0.58 cm $d^{-1}$) and declining to 0.26 cm $d^{-1}$ during R5 through R6. In contrast, no-till KB exhibited a simple negative linear relationship with water use rates declining from a high of 0.47 cm $d^{-1}$ during the R1 through R2 period to 0.22 cm $d^{-1}$ during R5 through R6. These results indicate LMs may increase SWC and utilize water more effectively, particularly when combining strip-till and herbicide management.

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**Abbreviations:** CER, carbon dioxide exchange rate; CF, creeping red fescue; DAE, days after emergence; DOY, day of the year; HI, harvest index; KB, Kentucky bluegrass; LAI, leaf area index; LM, living mulch; PM, postmaturity; PP, preplant; RP, reproductive; RWUE, reproductive water use efficiency; SOC, soil organic C; ST, soil temperature; SWC, soil water content; UAN, urea ammonium nitrate; VG, vegetative.

Harvesting maize (*Zea mays* L.) stover as a biomass feedstock could contribute between 68 and 232 million dry t annually toward U.S. biofuel production (Perlack et al., 2005). The range in these estimates accounts for variability in the genetic improvement of maize, harvesting technology, and sustainable production practices. However, continual removal of >25% of maize stover decreases soil productivity by lowering soil organic C (SOC) and removal effects on maize yield may be enhanced by soil type and topography (Blanco-Canqui and Lal, 2007). Doran et al. (1984) also reported lower maize yields when complete residue removal occurred but little or no effect on maize yield with 50% removal. Wilhelm et al. (2007) estimated that leaving 5.25 Mg stover $ha^{-1}$ $yr^{-1}$ is required to maintain SOC in no-till or conservation tillage in continuous maize compared to 7.58 Mg stover $ha^{-1}$ $yr^{-1}$ in moldboard plow. These estimates to maintain SOC are significantly higher than estimates to maintain soil erosion within the accepted tolerance (Wilhelm et al., 2007).

Innovative production system design may offer solutions to current constraints on sustainable biomass feedstock availability.

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Incorporating living mulches (LMs) into maize production systems can supply C to offset C harvested in stover, among other benefits. Living mulches have been used in maize-based cropping systems to supply forage, suppress weeds, and supply N (Elkins et al., 1979; Eberlein et al., 1992; Zemenchik et al., 2000; Singer et al., 2009). In continuous maize systems, a C3 LM species would be a logical functional group choice. A C3 species would exhibit dominant spring growth, which would reduce the competitive potential of the LM during the dominant summer growth period of the C4 species. Elkins et al. (1979) concluded it was possible to obtain good maize yields in chemically suppressed Kentucky bluegrass (KB) (*Poa pratensis* L.) or tall fescue (*Festuca arundinacea* Schreb.) while maintaining at least 50% of the grass sod. Eberlein et al. (1992) reported lower nonirrigated maize yields in a partially suppressed alfalfa (*Medicago sativa* L.) LM compared to a no-LM control and concluded that LM systems in the upper Midwest United States may be too risky without irrigation. Liedgens et al. (2004) reported lower soil water content (SWC) in the 0.3- to 0.9-m soil depth in maize growing in an Italian ryegrass (*Lolium multiflorum* Lam.) LM compared to a no-LM control, even after intense rainfall. Ochsner et al. (2010) reported higher mean SWC (0.01 $m^3 m^{-3}$) in maize growing in a kura clover (*Trifolium ambiguum* M. Bieb.) LM compared to a no-LM control; however, early season transpiration by the kura LM lowered SWCs compared to the control and the effect extended to a 1-m soil depth.

Living mulch cropping systems introduce the potential for higher risk of main crop yield reductions because different species are growing concurrently. Selecting contrasting functional groups with LM suppression management can mitigate potentially negative competitive effects. Furthermore, the presence of the LM on the soil surface may provide positive soil water effects late in the growing season when the maize crop relies on rainfall after stored soil water is depleted. A shaded LM minimally transpires, lowers soil water evaporation (Ochsner et al., 2010), and likely increases water infiltration compared to bare soil. We hypothesized that chemically suppressed grass LMs would not contribute to maize water stress as a result of soil water deficits in this continuous maize biomass production system. The specific objectives of this study were to quantify soil water dynamics and maize whole-plant water use in LMs compared to a no-LM control partitioned into growing season phases and maize phenology to understand the role of water and plant performance in these complex agronomic production systems.

## MATERIALS AND METHODS

Field research was conducted between 2008 and 2010 on the Iowa State University Agronomy and Agricultural Engineering Sorenson Research Farm near Ames, IA (42°0.7′ N, 93°46′ W), on a Nicollet (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) soil with approximately 0 to 2% slope. The research area was previously in a maize–soybean [*Glycine max* (L.) Merr.] rotation. Soybean was chopped into a harvest wagon and removed from the field in late July in 2006, and then the field was disked and field cultivated to prepare a seedbed for LM establishment. Living mulch species were planted 21 Aug. 2006 in ten 20-cm rows with double disk openers and 5-cm wide press wheels in a prepared seedbed and then rolled with a 2.1 m wide pulverizer and packer with 52 cm notched ductile iron roller wheels. Kentucky bluegrass (‘Troy’) and creeping red fescue (CF) (variety not stated) (*Festuca rubra* L.) were seeded at 49 and 56 kg $ha^{-1}$, respectively. Soil test levels in August 2006 in the surface 20 cm measured 21.8 mg $kg^{-1}$ P and 156 mg $kg^{-1}$ K using Mehlich-3, pH of 6.6, and 48 g $kg^{-1}$ organic matter. Maize was planted in the entire field on 14 May 2007 using a five row planter with 0.76 m rows at 81,510 seeds $ha^{-1}$.

The experimental design was a randomized incomplete block with LM species as the whole plot factor and tillage or herbicide in a 2 × 2 factorial arrangement as the subplot factor with four replicates. Treatments used in this study were a subset of treatments from the larger experiment and included a no-LM control, maize growing in a KB LM, and maize in a CF LM with four replicates. Plot size was 3.8 m wide by 22.8 m long. All treatments were managed using no-till. The control was maintained weed free using glyphosate [N-(phosphonomethyl) glycine] (Roundup WeatherMAX, Monsanto, St. Louis, MO) broadcast at a rate of 1.0 kg a.i. $ha^{-1}$ in solution with 187 L $ha^{-1}$. Living mulch plots had paraquat dichloride [1,1′-dimethly-4,4′-bipyridinium dichloride] (Gramoxone Inteon, Syngenta Crop Protection, Inc., Greensboro, NC) broadcast preemergence at a rate of 0.84 kg a.i. $ha^{-1}$ in solution with 281 L $ha^{-1}$ in 2008, 2009, and 2010. No paraquat dichloride was applied in the spring of 2007 to facilitate LM establishment, although two postemergence glyphosate applications were made. Additionally, LM plots received two postemergence glyphosate applications in 25-cm bands over the maize row at 1.0 kg a.i. $ha^{-1}$ in solution with 187 L $ha^{-1}$. Living mulches were managed similarly each year using herbicide suppression and were not harvested in any year. In the fall of each year approximately 30 d after maize harvest, LMs were mowed using a rotary mower to create a uniform LM canopy.

‘Pioneer Brand 34A20′ maize hybrid was planted in each subplot on 16 May 2008, 5 May 2009, and 29 Apr. 2010 at 86,450 seeds $ha^{-1}$ using a five-row planter in 0.76 m rows at a target seeding depth of 5 cm. A fertilizer point-injector was used to sidedress 202, 168, and 168 kg N $ha^{-1}$ as urea ammonium nitrate (UAN) in the entire experiment on 19, 4, and 1 June 2008, 2009, and 2010. In 2009 and 2010, an additional 39 kg N $ha^{-1}$ as UAN was applied at planting with a planter-disk opener. Soil fertility amendments were applied to the entire experiment in the fall each year by applying diammonium phosphate plus potash at a rate of 19–39–223 (N–P–K) kg $ha^{-1}$ with a coulter-knife injector.

Stevens Hydra Probe II Soil Moisture Sensors (Stevens Water Monitoring Systems, Inc., Portland, OR) were installed in the control, CF, and KB LM treatments. Sensors were buried in April 2008 at 15 and 45 cm in replicates 1, 3, and 4 approximately 3 m from the end of the plot and offset 38 cm from the nontrafficked center row. Data were collected every hour and averaged over a 24 h period to provide a daily reading for volumetric SWC ($m^3 m^{-3}$) and soil temperature (ST) (°C) using a CR5000 datalogger (Campbell Scientific, Inc., Logan, UT).

Maize phenology was determined from emergence to maturity following Ritchie et al. (1993). Six plants per subplot, three in row two and three in row four, were marked and staged weekly

Table 1. Average monthly air temperature and precipitation collected approximately 2 km from the experimental site†. Thirty-year averages were computed from data collected between 1975 and 2004.

| Month | Air temperature | | | | Precipitation | | | |
|---|---|---|---|---|---|---|---|---|
| | 2008 | 2009 | 2010 | 30-yr | 2008 | 2009 | 2010 | 30-yr |
| | °C | | | | mm | | | |
| Mar. | 1.0 | 3.8 | 4.0 | 2.8 | 71 | 103 | 38 | 53 |
| Apr. | 8.4 | 9.2 | 13.0 | 10.3 | 130 | 116 | 100 | 93 |
| May | 15.2 | 16.0 | 15.9 | 16.5 | 216 | 104 | 89 | 112 |
| June | 21.2 | 20.8 | 21.8 | 21.4 | 271 | 104 | 312 | 119 |
| July | 23.2 | 20.5 | 23.9 | 23.5 | 234 | 70 | 122 | 112 |
| Aug. | 21.5 | 20.9 | 23.8 | 22.1 | 53 | 123 | 396 | 120 |
| Sept. | 17.9 | 18.1 | 17.5 | 18.1 | 78 | 24 | 126 | 76 |
| Oct. | 11.6 | 7.9 | 13.3 | 11.1 | 92 | 186 | 12 | 61 |
| Nov. | 3.1 | 7.0 | 4.0 | 2.6 | 66 | 34 | 58 | 51 |

†NWS COOP site Ames 8WSW (near Ames, IA).

to determine vegetative growth stages. Kernel phenology during reproductive growth was assessed by removing 10 to 15 kernels per ear from ears on six plants. Leaf area index (LAI) was measured with an LAI-2000 Plant Canopy Analyzer (LI-COR, Inc., Lincoln, NE) at V6, V12, R1, and R3 in 2008, 2009, and 2010. Maize leaf area was determined by collecting one measurement above the maize canopy and four measurements diagonally across a nontrafficked interrow below the canopy. Carbon dioxide exchange rate (CER) (μmol $m^{-2}$ $s^{-1}$) and leaf transpiration (mmol $m^{-2}$ $s^{-1}$) were measured in 2008, 2009, and 2010 using a portable open path infrared gas analyzer (LI-6400, LI-COR, Inc.). Measurements were taken at V6, V12, R1, and R3 on four consecutive days, weather permitting, between 1030 and 1330 h. Three leaves per plot were measured on the adaxial surface of the upper most leaf with an exposed collar until silking (R1), when the leaf above the terminal ear was used for the remainder of the measurement period. The LI-6400 was set at a flow rate of 500 μmol $s^{-1}$, $CO_2$ concentration of 380 μmol $mol^{-1}$, and leaf boundary layer conductance of 2.84 mol $m^{-2}$ $s^{-1}$. Photosynthetically active radiation exceeded 1200 μmol $m^{-2}$ $s^{-1}$ during all measurements.

Whole-plant transpiration was measured from R1 to physiological maturity (R6) using Dynagage Sap Flow Sensors (Dynamax Inc., Houston, TX). Transpiration data are presented by growth stage using the phenology data. Sensors were installed on five consecutive maize plants approximately 30 cm above the soil surface in the nontrafficked center row of the KB and control plots in one replicate. Lower maize leaves and sheaths were removed to enhance sensor placement on the maize stem. Sensors were insulated with foam and covered with foil to minimize environmental fluctuations. In 2008, a combination of 25 and 19 mm sensors were used and in 2009 and 2010 only 19 mm sensors were used. Input voltage was set at 4.5 V for all sensors all years. Stem diameter was determined by averaging two measurements on opposite sides of the stem with electronic calipers approximately 30 cm above the soil surface. Sap flow was measured using an energy balance method determined by a constant heat source (Sakuratani, 1981). Sap flow was measured every 60 s and averaged every 12 min with a CR10X datalogger (Campbell Scientific, Inc.). Data collected from 0600 to 2000 h were used to calculate daily plant transpiration. All sensors were moved approximately every 17 d and placed on the next five consecutive plants of the center row. Data were converted from grams per day between 0600 and 2000 h to mm water depth during this time interval by multiplying by the plant density. In 2008 and 2009 maize plant densities used for these calculations were 8.66 and 7.67 plants $m^{-2}$. In 2010, 8.00 and 7.00 plants $m^{-2}$ were used for the control and KB treatments, respectively.

At R6, maize aboveground dry matter above the brace roots was sampled from 1.0 $m^2$ in each plot. Grain was separated from the stover to determine grain yield, stover dry matter, kernel number, and harvest index (HI). Stover was dried in a forced-air oven at 70°C to constant weight. Grain mass for reproductive water use efficiency (RWUE) is presented on a dry matter basis (ASAE, 2001). Reproductive water use efficiency was calculated as the dry grain mass divided by maize water use from R1 to R6. A self-propelled silage chopper was used to collect remaining aboveground maize grain and stover leaving approximately 8 cm stubble height. Precipitation and air temperature were downloaded from the Iowa Environmental Mesonet National Weather Service COOP 8WSW station located approximately 2 km from the research site (IEM, 2011) and are presented by month between March and September (Table 1).

Data were analyzed using SAS version 9.2.2 (SAS Institute, 2008). Soil water content at 15 and 45 cm and the 15 cm ST were divided into four distinct seasonal periods: preplant (PP) occurred from May 1 until maize emergence, vegetative (VG) occurred from emergence until maize reached reproductive growth, reproductive (RP) occurred from R1 to R6, and postmaturity (PM) occurred after R6 to November 30 each year. A first order autoregressive repeated measures model was used in PROC MIXED (SAS Institute, 2008) for SWC and ST with replicate as a random factor and groundcover as a fixed factor. Leaf area index, CER, and leaf transpiration were analyzed as a randomized complete block design using PROC MIXED with replicate as a random factor and groundcover as a fixed effect. Degrees of freedom for all data were adjusted using the Satterthwaite approximation and *p*-values were adjusted using Tukey's probability adjustments. Effects were considered significant if *p*-values were ≤0.05. Because sap flow data were only collected in one replicate, pooled standard errors were calculated to compare treatments (Walpole and Meyers, 1978).

# RESULTS AND DISCUSSION

## Soil Water Content and Soil Temperature

Soil water contents were affected by groundcover treatment in 2008 and 2010 but not in 2009 (Tables 2, 3, and 4; Fig. 1 through 6). In 2008 and 2010, above-average rainfall during the growing season occurred during consecutive months. In

Table 2. Probability values for volumetric soil water content (SWC) at the 15 and 45 cm depths, soil temperature (ST) at the 15 cm depth, leaf area index (LAI), carbon dioxide exchange rate (CER), and leaf transpiration rate (TR). Soil water and ST were collected during four seasonal intervals: preplanting (PP), vegetative (VG), reproductive (RP), and postmaturity (PM). Leaf area index, CER, and TR were collected at V6, V12, R1, and R3. All data were collected in maize without a living mulch (control) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) and managed with paraquat and no-tillage treatments near Ames, IA, in 2008.

| | SWC 15 cm | | | | SWC 45 cm | | | | ST 15 cm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | PP | VG | RP | PM | PP | VG | RP | PM | PP | VG | RP | PM |
| | $p > F$ | | | | | | | | | | | |
| Groundcover | 0.0992 | 0.0588 | 0.0688 | 0.0029 | 0.9833 | 0.9660 | 0.9401 | 0.8196 | 0.7316 | 0.0021 | 0.8279 | 0.9910 |
| | LAI | | | | CER | | | | TR | | | |
| | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 |
| Groundcover | 0.0001 | 0.0008 | 0.0323 | 0.5699 | 0.2852 | 0.9275 | 0.1987 | 0.5178 | 0.9172 | 0.8004 | 0.4431 | 0.9016 |
| | SWC 15 cm | | | | SWC 45 cm | | | | ST 15 cm | | | |
| | PP | VG | RP | PM | PP | VG | RP | PM | PP | VG | RP | PM |
| | $p > t$ | | | | | | | | | | | |
| Control vs. CF | 0.0916 | 0.0482 | 0.0762 | 0.0049 | 0.9983 | 0.9998 | 0.9504 | 0.8109 | 0.7119 | 0.0019 | 0.8531 | 0.9901 |
| Control vs. KB | 0.2659 | 0.3743 | 0.1604 | 0.0081 | 0.9916 | 0.9696 | 1.0000 | 0.9778 | 0.9424 | 0.7364 | 0.8564 | 0.9970 |
| CF vs. KB | 0.7027 | 0.3766 | 0.8523 | 0.9571 | 0.9825 | 0.9742 | 0.9497 | 0.9053 | 0.8871 | 0.7758 | 1.0000 | 0.9980 |
| | LAI | | | | CER | | | | TR | | | |
| | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 |
| Control vs. CF | 0.0001 | 0.0006 | 0.0593 | 0.5698 | 0.7249 | 0.9205 | 0.5876 | 0.7658 | 0.9094 | 0.8571 | 0.5909 | 0.8943 |
| Control vs. KB | 0.0007 | 0.0092 | 0.9462 | 0.8388 | 0.6769 | 0.9821 | 0.1720 | 0.8951 | 0.9795 | 0.9956 | 0.4527 | 0.9844 |
| CF vs. KB | 0.0636 | 0.0490 | 0.0401 | 0.8798 | 0.2541 | 0.9765 | 0.6796 | 0.4908 | 0.9730 | 0.8106 | 0.9717 | 0.9571 |

contrast, multiple months during the 2009 growing season experienced below-normal rainfall. In 2008, groundcover significantly affected SWC at the 15 cm soil depth during VG and PM. The control had lower SWC than CF during VG and PM and lower SWC than KB during PM in 2008. No differences were detected between CF and KB in 2008. During VG, the control averaged 0.3687 $m^3\ m^{-3}$ compared with 0.3879 $m^3\ m^{-3}$ in CF. During PM, CF and KB had 0.3696 and 0.3681 $m^3\ m^{-3}$ SWC compared with 0.3473 $m^3\ m^{-3}$ in the control. Soil water contents in the control trended lower compared with the groundcover treatment during PP ($p$ = 0.0992) and RP ($p$ = 0.0688) in 2008. "Field capacity" for this Nicollet soil was estimated at 0.359 $m^3\ m^{-3} \pm 0.029$ SD, while "wilting point" was estimated at 0.148 $m^3\ m^{-3} \pm 0.011$ SD (Sally Logsdon, personal communication, 2011).

No significant treatment effect was detected at the 45-cm soil depth in 2008. Soil water content never decreased below 0.3840 $m^3\ m^{-3}$ in 2008 at 45 cm (Fig. 2). Even at the 15-cm soil depth, SWC never declined below 0.3200 $m^3\ m^{-3}$ because of the frequency and amount of rainfall (Fig. 1). Average monthly rainfall in 2008 during April, May, June, and July was 40, 93, 128, and 109% above normal. Groundcover affected ST during VG ($p$ = 0.0021) with ST in the control (23.8°C) significant compared to CF (16.8°C) during VG ($p$ = 0.0019) (Tables 2 and 5). Soil temperature at the 15 cm soil depth ranged between 12.7 and 13.2°C during PP, 18.3 to 19.9°C during RP, and 7.6 to 8.3°C during PP although differences were not significant.

In 2009, there were no significant effects of groundcover on SWC at either depth during the four growth periods (Table 3). Additionally, ST was not affected by groundcover during any growth period. Soil water content at the 15-cm soil depth trended lower in the CF treatment starting at day of the year (DOY) 197 until DOY 239. Soil water content dropped to 0.2074 $m^3\ m^{-3}$ in the CF treatment compared with 0.2513 and 0.2498 $m^3\ m^{-3}$ in the control and KB on DOY 219 (Fig. 3). At 45 cm in 2009, SWC also trended lower in the control compared with the LM treatments during three of the four seasonal intervals ($p$ = 0.1171 during VG, $p$ = 0.1371 during RP, and $p$ = 0.1478 during PP). Although statistical differences were not detected, it appeared the LM treatments increased the water holding capacity of the soil. For example, the 6 cm of rainfall that occurred on DOY 146 and 147 increased SWC to 0.4013 $m^3\ m^{-3}$ in the control (Fig. 4). Within 3 d, however, SWC declined to 0.3588 $m^3\ m^{-3}$ in the control while SWC remained above 0.39 $m^3\ m^{-3}$ in the LM treatments. In May, June, and July 2009 rainfall was 7, 13, and 37% below normal, while August had 3% above-normal rainfall.

Rainfall during the 2010 growing season was above normal even though May had 21% below-normal rainfall. June had 262% above-normal rainfall and August received 330% higher than normal rainfall. Soil water content was affected by groundcover during all seasonal intervals at both soil depths except during VG at the 15-cm soil depth. Soil water content was higher in CF than the control during all significant intervals. Soil water content was higher in KB than the control during RP and PP at the 15-cm soil depth and during VG, RP, and PP at the 45-cm soil depth. Soil water content was higher in CF than KB during VG and PR at 45 cm. Differences in SWC at 15 cm between CF and the control during PP were 4% and increased to 10% higher during PM (Fig. 5). Differences in SWC were as high as 4%

Table 3. Probability values for volumetric soil water content (SWC) at the 15 and 45 cm depths, soil temperature (ST) at the 15 cm depth, leaf area index (LAI), carbon dioxide exchange rate (CER), and leaf transpiration rate (TR). Soil water and ST were collected during four seasonal intervals: preplanting (PP), vegetative (VG), reproductive (RP), and postmaturity (PM). Leaf area index, CER, and TR were collected at V6, V12, R1, and R3. All data were collected in maize without a living mulch (control) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) and managed with paraquat and no-tillage treatments near Ames, IA, in 2009.

| | SWC 15 cm | | | | SWC 45 cm | | | | ST 15 cm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | PP | VG | RP | PM | PP | VG | RP | PM | PP | VG | RP | PM |
| | p > F | | | | | | | | | | | |
| Groundcover | 0.6072 | 0.9274 | 0.6282 | 0.7571 | 0.6075 | 0.1171 | 0.1371 | 0.1478 | 0.9843 | 0.9155 | 0.9762 | 0.9947 |
| | LAI | | | | CER | | | | TR | | | |
| | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 |
| Groundcover | 0.0457 | 0.2186 | 0.5517 | 0.3026 | 0.9531 | 0.8263 | 0.4538 | 0.7102 | 0.9973 | 0.8647 | 0.9464 | 0.5622 |
| | SWC 15 cm | | | | SWC 45 cm | | | | ST 15 cm | | | |
| | PP | VG | RP | PM | PP | VG | RP | PM | PP | VG | RP | PM |
| | p > t | | | | | | | | | | | |
| Control vs. CF | 0.5816 | 0.9240 | 0.6134 | 0.7375 | 0.6810 | 0.1483 | 0.1365 | 0.1528 | 0.9962 | 0.9097 | 0.9738 | 0.9997 |
| Control vs. KB | 0.8530 | 0.9922 | 0.9492 | 0.9210 | 0.6359 | 0.1542 | 0.2517 | 0.2494 | 0.9951 | 0.9601 | 0.9934 | 0.9967 |
| CF vs. KB | 0.8669 | 0.9624 | 0.7893 | 0.9265 | 0.9959 | 0.9989 | 0.8242 | 0.8915 | 0.9827 | 0.9880 | 0.9934 | 0.9947 |
| | LAI | | | | CER | | | | TR | | | |
| | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 |
| Control vs. CF | 0.0390 | 0.1958 | 0.5355 | 0.2755 | 0.9567 | 0.8695 | 0.9774 | 0.8049 | 0.9987 | 0.8664 | 0.9673 | 0.6775 |
| Control vs. KB | 0.2272 | 0.6428 | 0.9308 | 0.6902 | 0.9660 | 0.8369 | 0.5910 | 0.7145 | 0.9971 | 0.9121 | 0.9464 | 0.5768 |
| CF vs. KB | 0.3976 | 0.5711 | 0.7387 | 0.6788 | 0.9994 | 0.9980 | 0.4677 | 0.9866 | 0.9997 | 0.9942 | 0.9973 | 0.9854 |

at 15 cm in KB than the control at RP and 8% higher during PM. At 45 cm, CF had 16% higher SWC than the control during PP and 21 and 17% higher SWC during RP and PM. Soil water content in KB was 7, 13, and 18% higher than the control during VG, RP, and PM at 45 cm. Soil water content was also 7 and 9% higher in CF than KB during VG and RP at 45 cm in 2010. Similarly to observations in 2009, SWC responses in 2010 indicate that LMs may increase the soil water holding capacity. Between DOY 219 and 222, 23 cm of rainfall was received at the experimental site and SWC increased above 0.4000 $m^3\ m^{-3}$ in the control and CF treatments (Fig. 6). By DOY 226 SWC in the control rapidly declined to 0.3503 $m^3\ m^{-3}$ while CF and KB were 0.3984 and 0.4031 $m^3\ m^{-3}$. Similar responses also occurred between DOY 243 and 248 toward the end of RP and DOY 269 and 274 during the PM interval.

Table 4. Probability values for volumetric soil water content (SWC) at the 15 and 45 cm depths, soil temperature (ST) at the 15 cm depth, leaf area index (LAI), carbon dioxide exchange rate (CER), and leaf transpiration rate (TR). Soil water and ST were collected during four seasonal intervals: preplanting (PP), vegetative (VG), reproductive (RP), and postmaturity (PM). Leaf area index, CER, and TR were collected at V6, V12, R1, and R3. All data were collected in maize without a living mulch (control) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) and managed with paraquat and no-tillage treatments near Ames, IA, in 2010.

| | SWC 15 cm | | | | SWC 45 cm | | | | ST 15 cm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | PP | VG | RP | PM | PP | VG | RP | PM | PP | VG | RP | PM |
| | p > F | | | | | | | | | | | |
| Groundcover | 0.0509 | 0.5923 | 0.0001 | 0.0001 | 0.0003 | 0.0001 | 0.0001 | 0.0001 | 0.9757 | 0.9798 | 0.8033 | 0.9965 |
| | LAI | | | | CER | | | | TR | | | |
| | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 |
| Groundcover | 0.0485 | 0.0118 | 0.0563 | 0.6212 | 0.2405 | 0.6201 | 0.5134 | 0.6833 | 0.5461 | 0.7214 | 0.0566 | 0.9926 |
| | SWC 15 cm | | | | SWC 45 cm | | | | ST 15 cm | | | |
| | PP | VG | RP | PM | PP | VG | RP | PM | PP | VG | RP | PM |
| | p > t | | | | | | | | | | | |
| Control vs. CF | 0.0485 | 0.7411 | 0.0001 | 0.0001 | 0.0002 | 0.0001 | 0.0001 | 0.0001 | 0.9949 | 1.0000 | 0.8117 | 0.9963 |
| Control vs. KB | 0.6788 | 0.5672 | 0.0552 | 0.0001 | 0.0938 | 0.0259 | 0.0001 | 0.0001 | 0.9914 | 0.9837 | 0.8609 | 0.9985 |
| CF vs. KB | 0.2868 | 0.8525 | 0.1608 | 0.1310 | 0.1158 | 0.0018 | 0.0001 | 0.6573 | 0.9734 | 0.9829 | 0.9948 | 0.9995 |
| | LAI | | | | CER | | | | TR | | | |
| | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 |
| Control vs. CF | 0.0470 | 0.0108 | 0.0558 | 0.5962 | 0.3415 | 0.6496 | 0.5215 | 0.6685 | 0.6183 | 0.7017 | 0.0540 | 0.9932 |
| Control vs. KB | 0.1320 | 0.4310 | 0.1405 | 0.8997 | 0.9743 | 0.9966 | 0.6415 | 0.9533 | 0.9983 | 0.9385 | 0.6945 | 0.9999 |
| CF vs. KB | 0.7058 | 0.0497 | 0.7557 | 0.8398 | 0.2628 | 0.6944 | 0.9744 | 0.8307 | 0.5871 | 0.8807 | 0.1561 | 0.9947 |

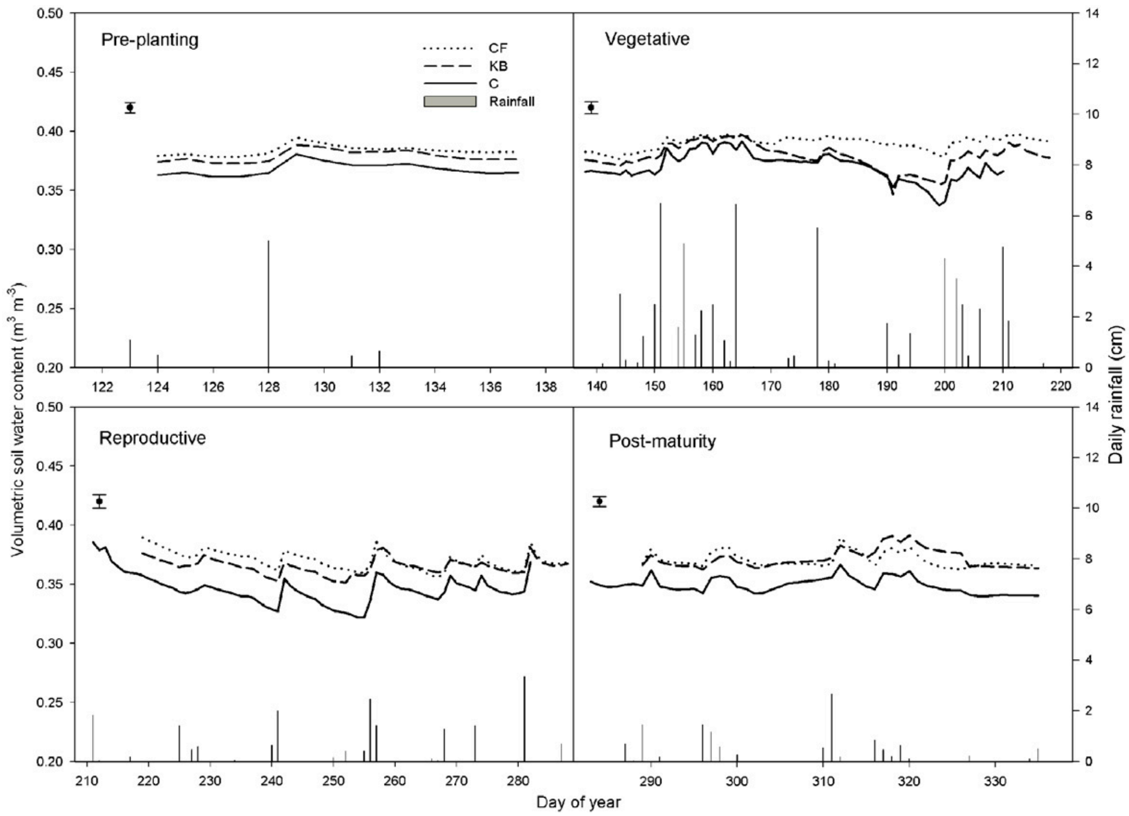


Figure 1. Daily soil water content at the 15 cm depth and daily rainfall for continuous maize grown without a living mulch (control [C]) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) during four seasonal intervals (preplanting, vegetative, reproductive, and postmaturity) in 2008 near Ames, IA. Vertical error bar is the standard error to compare treatments within an interval.

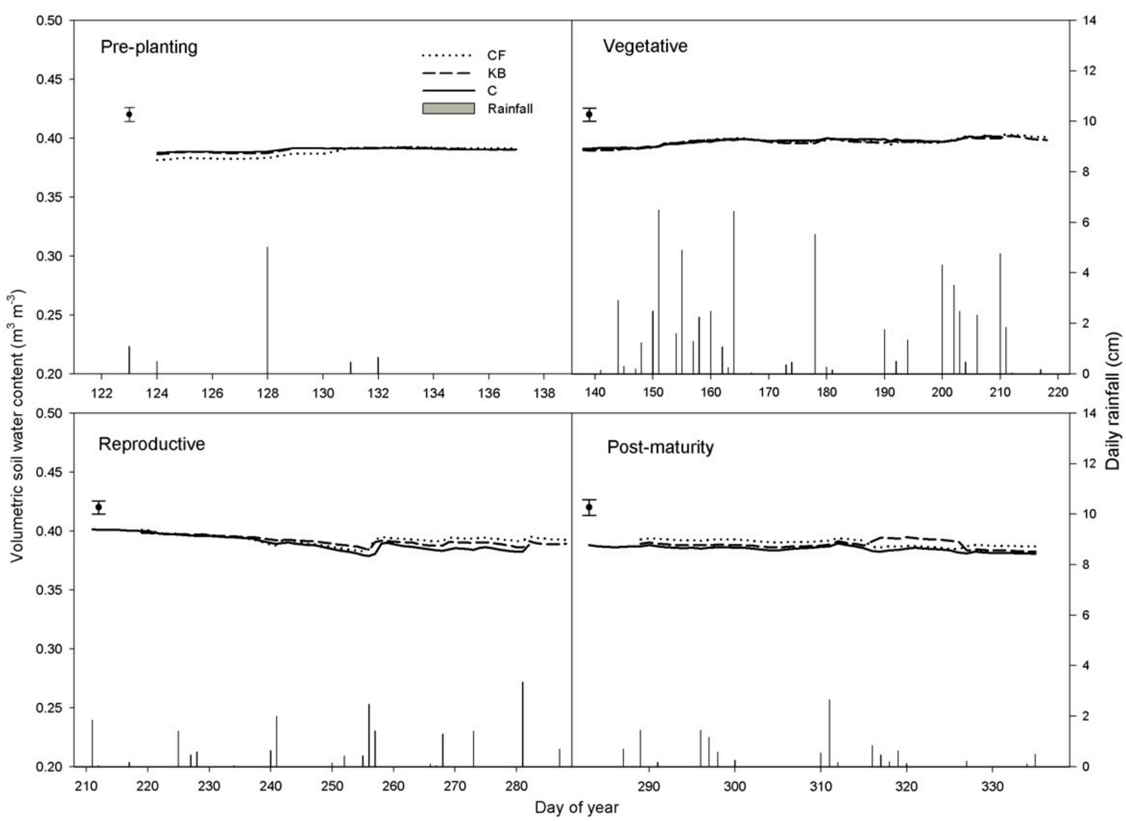


Figure 2. Daily soil water content at the 45 cm depth and daily rainfall for continuous maize grown without a living mulch (control [C]) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) during four seasonal intervals (preplanting, vegetative, reproductive, and postmaturity) in 2008 near Ames, IA. Vertical error bar is the standard error to compare treatments within an interval.

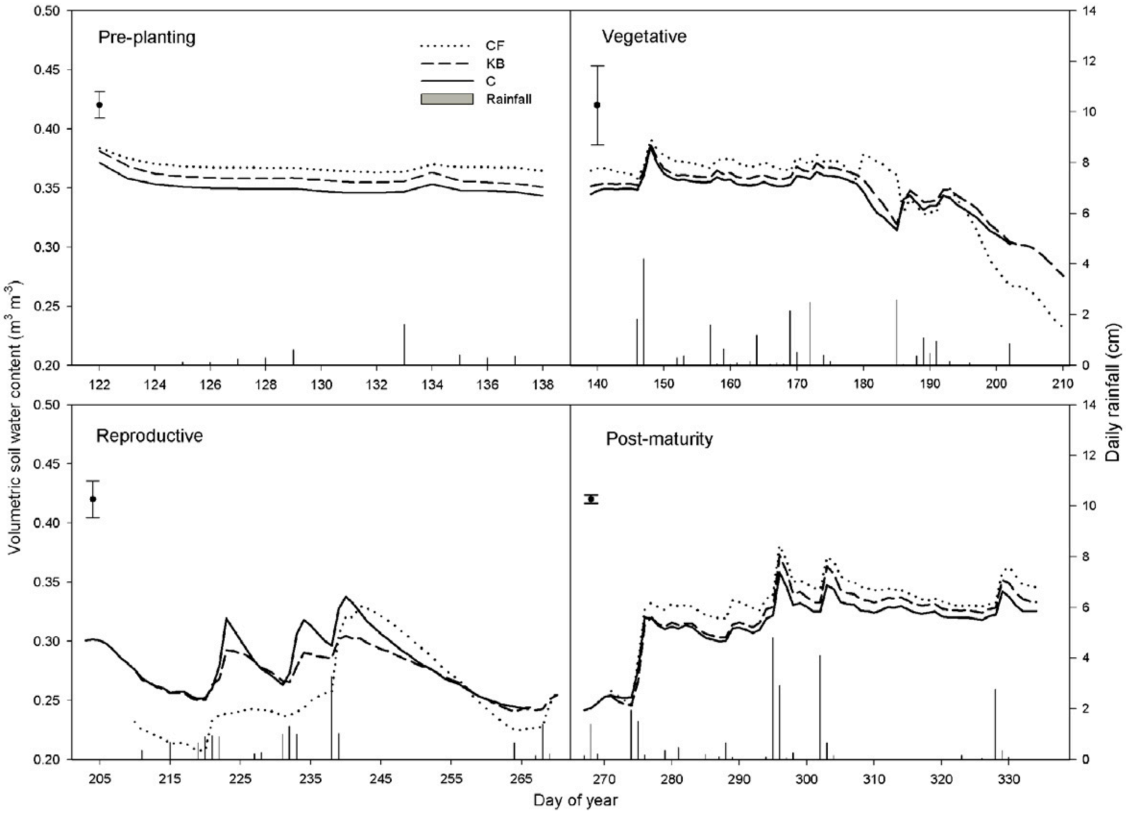


Figure 3. Daily soil water content at the 15 cm depth and daily rainfall for continuous maize grown without a living mulch (control [C]) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) during four seasonal intervals (preplanting, vegetative, reproductive, and postmaturity) in 2009 near Ames, IA. Vertical error bar is the standard error to compare treatments within an interval.

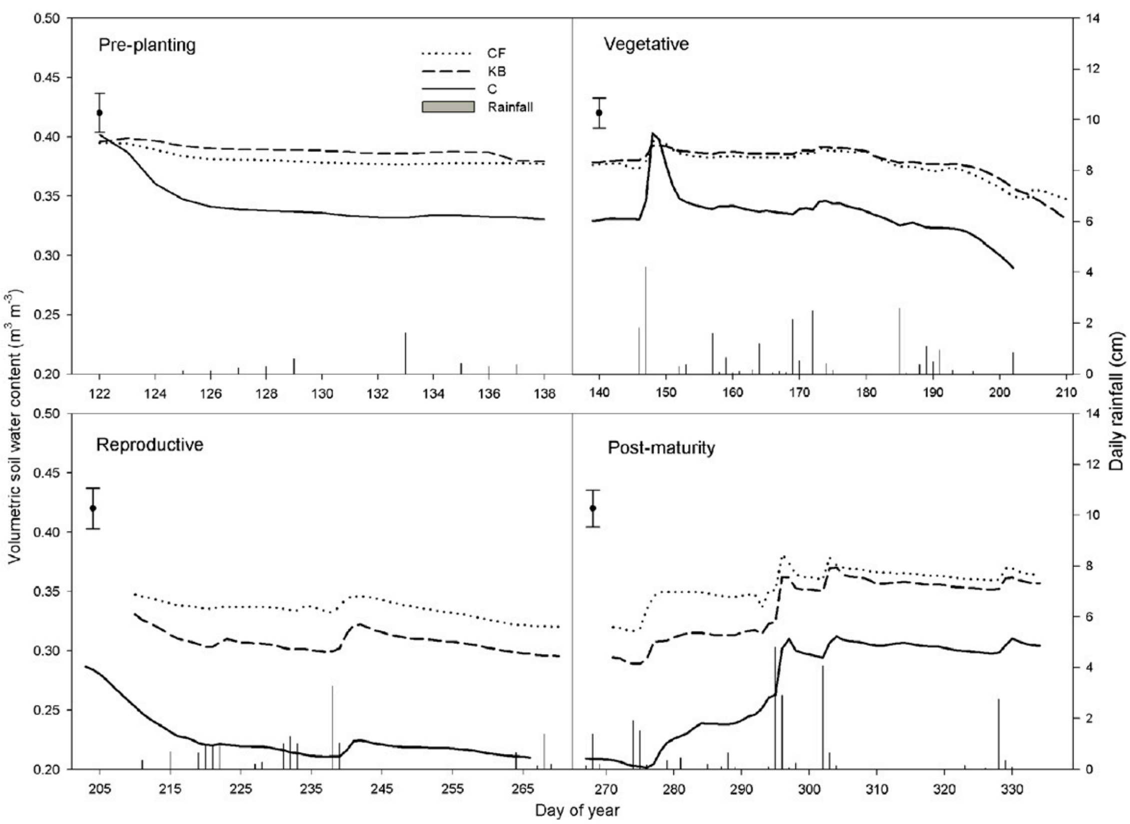


Figure 4. Daily soil water content at the 45 cm depth and daily rainfall for continuous maize grown without a living mulch (control [C]) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) during four seasonal intervals (preplanting, vegetative, reproductive, and postmaturity) in 2009 near Ames, IA. Vertical error bar is the standard error to compare treatments within an interval.

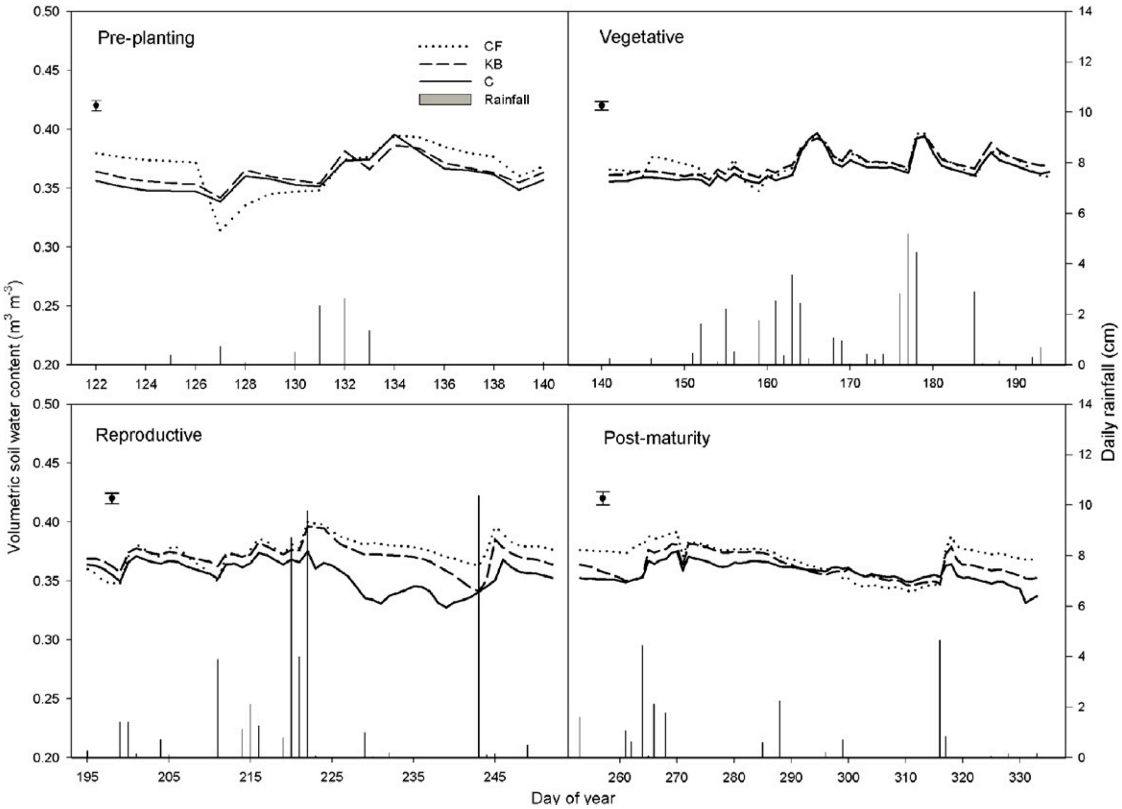


Figure 5. Daily soil water content at the 15 cm depth and daily rainfall for continuous maize grown without a living mulch (control [C]) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) during four seasonal intervals (preplanting, vegetative, reproductive, and postmaturity) in 2010 near Ames, IA. Vertical error bar is the standard error to compare treatments within an interval.

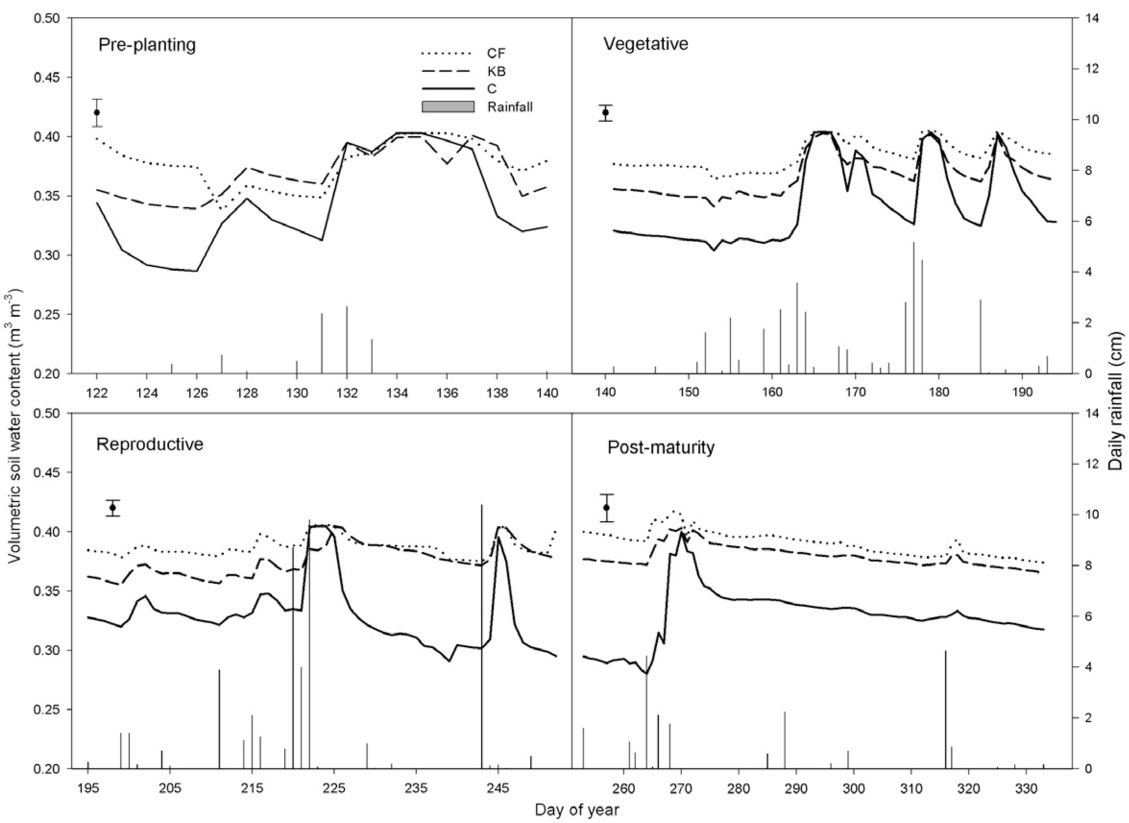


Figure 6. Daily soil water content at the 45 cm depth and daily rainfall for continuous maize grown without a living mulch (control [C]) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) during four seasonal intervals (preplanting, vegetative, reproductive, and postmaturity) in 2010 near Ames, IA. Vertical error bar is the standard error to compare treatments within an interval.

Table 5. Treatment means for volumetric soil water content (SWC, $m^3 m^{-3}$) at the 15 and 45 cm depths, soil temperature (ST, °C) at 15 cm, leaf area index (LAI), carbon dioxide exchange rate (CER, $\mu mol m^{-2} s^{-1}$), and transpiration (TR, $mmol m^{-2} s^{-1}$). Soil water and ST were collected during four seasonal intervals: preplanting (PP), vegetative (VG), reproductive (RP), and postmaturity (PM). Leaf area index, CER, and TR where collected at V6, V12, R1, and R3. All data were collected in maize without a living mulch (control) and maize grown in a living mulch of creeping red fescue (CF) or Kentucky bluegrass (KB) and managed with paraquat and no-tillage treatments near Ames, IA in 2008, 2009, and 2010.

| | SWC 15 cm | | | | SWC 45 cm | | | | ST 15 cm | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Treatment | PP | VG | RP | PM | PP | VG | RP | PM | PP | VG | RP | PM |
| **2008** | | | | | | | | | | | | |
| Control | 0.3656 | 0.3687 | 0.3522 | 0.3473 | 0.3892 | 0.3963 | 0.3933 | 0.3840 | 13.2 | 23.8 | 18.3 | 7.6 |
| CF | 0.3822 | 0.3879 | 0.3711 | 0.3696 | 0.3897 | 0.3962 | 0.3956 | 0.3899 | 12.7 | 16.8 | 19.9 | 8.3 |
| KB | 0.3770 | 0.3782 | 0.3669 | 0.3681 | 0.3882 | 0.3945 | 0.3932 | 0.3859 | 13.0 | 20.1 | 19.8 | 8.0 |
| **2009** | | | | | | | | | | | | |
| Control | 0.3563 | 0.3273 | 0.2758 | 0.2995 | 0.3631 | 0.3184 | 0.2467 | 0.2599 | 12.6 | 17.4 | 18.9 | 10.3 |
| CF | 0.3732 | 0.3092 | 0.2497 | 0.3184 | 0.3849 | 0.3657 | 0.3337 | 0.3451 | 12.5 | 18.4 | 19.1 | 10.4 |
| KB | 0.3650 | 0.3217 | 0.2676 | 0.3091 | 0.3871 | 0.3648 | 0.3127 | 0.3284 | 12.6 | 18.1 | 19.0 | 10.0 |
| **2010** | | | | | | | | | | | | |
| Control | 0.3544 | 0.3654 | 0.3539 | 0.3365 | 0.3271 | 0.3394 | 0.3187 | 0.3149 | 12.7 | 20.2 | 21.7 | 9.7 |
| CF | 0.3689 | 0.3683 | 0.3769 | 0.3727 | 0.3902 | 0.3886 | 0.4026 | 0.3794 | 12.7 | 20.2 | 22.3 | 10.4 |
| KB | 0.3599 | 0.3704 | 0.3679 | 0.3655 | 0.3622 | 0.3633 | 0.3665 | 0.3837 | 12.8 | 20.6 | 22.2 | 10.1 |
| | LAI | | | | CER | | | | TR | | | |
| **2008** | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 | V6 | V12 | R1 | R3 |
| Control | 1.61 | 2.68 | 2.38 | 1.66 | 45.3 | 38.1 | 35.7 | 25.2 | 8.9 | 6.4 | 6.1 | 3.7 |
| CF | 0.17 | 1.13 | 1.83 | 1.38 | 43.9 | 39.1 | 33.7 | 26.7 | 8.0 | 6.7 | 5.7 | 3.9 |
| KB | 0.57 | 1.76 | 2.44 | 1.51 | 48.6 | 38.5 | 31.9 | 24.2 | 8.5 | 6.4 | 5.6 | 3.7 |
| **2009** | | | | | | | | | | | | |
| Control | 0.71 | 3.69 | 4.42 | 3.44 | 45.4 | 32.4 | 33.1 | 28.4 | 7.7 | 6.4 | 6.5 | 4.3 |
| CF | 0.38 | 2.95 | 4.02 | 3.01 | 43.5 | 33.4 | 32.8 | 29.5 | 7.6 | 6.8 | 6.7 | 4.6 |
| KB | 0.52 | 3.35 | 4.29 | 3.23 | 43.7 | 33.5 | 34.7 | 29.8 | 7.5 | 6.7 | 6.8 | 4.7 |
| **2010** | | | | | | | | | | | | |
| Control | 0.67 | 3.32 | 3.59 | 2.62 | 43.9 | 31.7 | 30.9 | 24.3 | 7.6 | 5.4 | 7.3 | 6.2 |
| CF | 0.33 | 2.36 | 2.84 | 2.28 | 41.2 | 29.2 | 32.8 | 22.1 | 7.3 | 5.0 | 8.5 | 6.1 |
| KB | 0.42 | 3.03 | 3.03 | 2.47 | 44.2 | 31.5 | 32.5 | 23.6 | 7.7 | 5.3 | 7.6 | 6.2 |

Ochsner et al. (2010) calculated a water balance for no-till maize and maize growing in a kura clover LM. They reported that maize growing in a kura clover LM increases the probability that maize may experience water stress, especially when rainfall in late spring is below normal. They also found that SWC was lower in the control than the LM treatment later in the growing season at the time of maximum water depletion by maize and attributed this difference to delayed maize root development, which reduced its ability to utilize soil moisture (Ochsner et al., 2010). Liedgens et al. (2004) reported that an Italian ryegrass LM in maize lowered deep percolation at least 40% compared with maize alone. They also found that the maize LM treatment lowered SWC in the 0.3- to 0.9-m soil depth compared with the control, even after intense rainfall. Liedgens et al. (2004) concluded that the LM lowered water and N availability and competition for these resources explained the decrease in the growth and yield of the maize plants. Eberlein et al. (1992) also reported that water stress from an alfalfa LM dramatically reduced maize grain yields in the absence of irrigation and concluded that the routine use of LMs was too risky in much of the upper Midwest United States. In contrast, Zemenchik et al. (2000) reported that a kura clover LM compared to a control did not decrease soil moisture to a 45-cm soil depth either year of their 2-yr study in the upper Midwest United States and concluded kura clover could be used as a LM with little or no whole-plant or grain yield reduction.

## Leaf Area Index

In 2008, groundcover significantly affected LAI at V6, V12, and R1 (Table 2). The control had higher LAI than CF and KB at V6 and V12, and CF had lower LAI than KB at V12 and R1. Living mulch height was equal to maize height at V6 in the CF and KB treatments due to a delayed initial herbicide application until May because of excessively wet soil conditions (data not presented). At V6, the control LAI was 1.61 compared with 0.57 in KB and 0.17 in CF (Table 5). By R1, KB had attained an LAI of 2.44 compared with 2.38 in the control, while CF LAI remained low at 1.83. Peak LAI in 2008 was lowered by hail at the experimental site on 27 July, which occurred at or close to the R1 growth stage, depending on the treatment. In 2009, groundcover only affected LAI at V6 (Table 3). The only significant treatment comparison was between the control and CF at V6 ($p = 0.0390$). Initial herbicide application in April 2009 minimized competition between maize and the

Table 6. Maize transpiration (±SE) and day of year growth stage interval during reproductive growth in 2008, 2009, and 2010 near Ames, IA, for the control without a living mulch and maize growing in Kentucky bluegrass. Reproductive growth stages R1, R2, R3, R4, R5, and R6 correspond to silking, blister, milk, dough, dent, and physiological maturity.

| | Control | | | Kentucky bluegrass | | |
|---|---|---|---|---|---|---|
| R stage | Transpiration | Interval | Rate | Transpiration | Interval | Rate |
| | cm | d | cm d$^{-1}$ | cm | d | cm d$^{-1}$ |
| | | | 2008 | | | |
| 1–2 | 6.4 ± 0.10 | 211–221 | 0.58 | 3.3 ± 0.10 | 219–226 | 0.41 |
| 2–3 | 6.3 ± 0.07 | 222–233 | 0.53 | 4.1 ± 0.07 | 227–238 | 0.34 |
| 3–4 | 5.6 ± 0.09 | 234–245 | 0.47 | 2.7 ± 0.09 | 239–246 | 0.34 |
| 4–5 | 2.8 ± 0.05 | 246–254 | 0.31 | 1.9 ± 0.05 | 247–260 | 0.14 |
| 5–6 | 5.1 ± 0.07 | 255–284 | 0.17 | 3.9 ± 0.07 | 261–289 | 0.13 |
| Total | 26.2 ± 0.07 | 74 | 0.41 | 15.5 ± 0.07 | 71 | 0.27 |
| | | | 2009 | | | |
| 1–2 | 10.0 ± 0.12 | 203–217 | 0.67 | 9.5 ± 0.12 | 203–220 | 0.53 |
| 2–3 | 2.0 ± 0.09 | 218–222 | 0.40 | 2.7 ± 0.09 | 221–226 | 0.45 |
| 3–4 | 3.1 ± 0.08 | 223–228 | 0.52 | 2.7 ± 0.08 | 227–234 | 0.34 |
| 4–5 | 3.5 ± 0.08 | 229–237 | 0.39 | 3.6 ± 0.08 | 235–245 | 0.33 |
| 5–6 | 8.8 ± 0.09 | 238–267 | 0.29 | 7.5 ± 0.09 | 246–271 | 0.29 |
| Total | 27.4 ± 0.09 | 65 | 0.45 | 26.0 ± 0.09 | 69 | 0.39 |
| | | | 2010 | | | |
| 1–2 | 2.9 ± 0.08 | 196–201 | 0.48 | 2.9 ± 0.08 | 196–201 | 0.48 |
| 2–3 | 6.7 ± 0.09 | 202–216 | 0.45 | 6.4 ± 0.09 | 202–216 | 0.43 |
| 3–4 | 2.7 ± 0.11 | 217–221 | 0.54 | 5.4 ± 0.11 | 217–229 | 0.42 |
| 4–5 | 6.2 ± 0.08 | 222–236 | 0.41 | 2.1 ± 0.08 | 230–236 | 0.30 |
| 5–6 | 2.6 ± 0.08 | 237–244 | 0.33 | 2.0 ± 0.08 | 237–244 | 0.25 |
| Total | 21.1 ± 0.09 | 49 | 0.44 | 18.8 ± 0.09 | 49 | 0.38 |

LMs and allowed maize in the LM treatments to develop similar canopies. Peak LAI in 2009 ranged from 4.02 in CF at R1 to 4.42 in the control at R1. In 2010, groundcover was significant for LAI at the first three sampling dates but not at R3 (Table 4). No differences were detected between the control and KB, although CF had lower LAI than the control at V6, V12, and R1 and lower LAI than KB at V12. Peak LAI in 2010 occurred at R1 for the control (3.59) and CF (2.84) and at V12 and R1 for KB (3.03).

## Carbon Dioxide Exchange Rate and Leaf Transpiration

Groundcover did not affect maize CER any year (Tables 2, 3, and 4). Peak CER occurred at V6 all years (Table 5), which is similar to results presented by Singer et al. (2007). Maize exhibited similar CER at V12 and R1 and then CER declined during R3. Groundcover did not affect leaf transpiration in 2008 or 2009 (Tables 2 and 3). In 2010 at the R1 growth stage, CF had higher leaf transpiration than the control. Leaf transpiration responded more to air temperature than treatment during the three study years. For example, the highest readings in 2008 occurred at the V6 sampling period in early to mid July (Table 5). Air temperatures for the month of July 2008 averaged 23.2°C and were the highest monthly air temperatures during the 2008 growing season. In 2010, leaf transpiration peaked at the R1 sampling period and were the highest readings at R3 during the 3-yr study. Air temperatures in July and August 2010 were above normal and were the highest during the 2010 growing season. Maize response to these abiotic conditions was not limited by water, as the 2008 and 2010 growing seasons experienced above-normal to excessive rainfall.

## Whole-Plant Water Use

Maize whole-plant transpiration was measured throughout reproductive growth (silking to physiological maturity) in the control and KB treatments all years (Table 6). The duration of the reproductive period varied between 49 and 74 d for the control and 49 and 71 d for maize growing in a KB LM. In 2008, the combination of late planting, hail, and a later than normal autumn killing freeze contributed to the extended grain-filling period. In 2010, above-normal air temperatures during reproductive growth accelerated the grain-filling period with a corresponding decrease in maize water use.

Total whole-plant transpiration in the control in 2008 was 26.2 ± 0.07 cm during 74 d of reproductive growth compared with 15.5 ± 0.07 cm during 71 d in the KB treatment. Above-normal rainfall during the maize vegetative growth period significantly delayed phenological development and yield potential of maize in the LM treatment. Maize in the control had greater transpiration during all reproductive intervals in 2008 and greater total water use. During the R1 to R6 growth stages, maize water use per day in the control averaged 0.41 cm compared with 0.27 in the KB treatment. Although maize plants in KB had similar LAI to control plants at the R3 growth stage (1.51 vs. 1.66), maize plants were significantly smaller in the KB treatment compared with the control. Stover dry matter was 31% lower in KB than the control in 2008 and kernel number per square meter was 25% lower although HI was 0.57 compared with 0.56 in the control. Consequently, reductions in plant dry matter and kernel number lowered grain yield in 2008 in the KB treatment (Table 7). However, a concomitant reduction in whole-plant water use resulted in a 21% higher RWUE in the KB treatment compared with the control. Cox et al. (1990) also reported 29% lower kernel number in maize in an undrained no-till treatment compared to a no-till drained treatment in a wet year with 74 and 93% higher rainfall than the 30-yr average in June and July.

Although RWUE was greater in the KB treatment in 2008, this was achieved through lower productivity. The goal of this production system is not necessarily to increase use efficiency at the expense of reduced productivity. We agree with the conclusions of Blum (2009) and strive for effective water use. In another KB treatment in this study that utilized fall strip-till with all other management similar, maize yielded 966 g $m^{-2}$ dry grain mass and would have an RWUE between 37 and 62 g grain $cm^{-1}$ water, assuming whole-plant water use was between 15.5 and 26.2 cm. Harvest index in this treatment was 0.59 compared with 0.56 in the control. The higher yield in the KB strip-till treatment compared to the KB no-till treatment is likely explained by greater infiltration and surface water drainage, which minimized the time maize roots were exposed to anaerobic or near anaerobic conditions during periods of excessive rainfall during vegetative growth. These periods of excessive rainfall delayed growth significantly. In 2008, the control attained 50% silking on DOY 211 compared with DOY 221 in the no-till KB treatment and DOY 214 in the strip-till KB treatment. Kovar et al. (2011) reported that an interrow knife injected manure treatment increased rainfall required to produce runoff by 94% compared to a no-till control in the fall. In the spring the same comparison was 62%, although it was not statistically significant. Cassel and Wagger (1996) reported that cumulative infiltration without irrigation in an untrafficked interrow was increased using fall chisel tillage (22 cm depth) by 60 and 138% each year of a 2-yr study compared with no-till. In the present study, the fall strip-till treatment tilled a narrow band over the future row to approximately a 20- to 25-cm soil depth, which likely enhanced infiltration, drainage, and maize root proliferation.

In 2009, maize in the KB treatment (26.0 ± 0.09 cm) also transpired less water during reproductive growth than the control (27.4 ± 0.09 cm) in 69 and 65 d, respectively. Water use during the R1 through R2 interval were the highest recorded during the three year study. The control averaged 0.67 cm $d^{-1}$ and the KB treatment averaged 0.53 cm $d^{-1}$. The high water use during this period combined with less than 1 cm of rainfall rapidly depleted soil water and likely contributed to lower transpiration rates in the control during the R2 through R3 growth interval (0.40 cm $d^{-1}$) than the KB treatment. The same response was not observed in the LM treatment, which averaged 0.45 cm $d^{-1}$ during the R2 through R3 interval. Similar LAI was measured in the control and KB at R1 (4.42 vs. 4.29) and again at R3 (3.44 vs. 3.23) in 2009. Differences in whole-plant transpiration may be related to SWC at the 45 cm soil depth, which averaged 0.2467 $m^3$ $m^{-3}$ in the control and 0.3127 $m^3$ $m^{-3}$ in KB during reproductive growth. Whole-plant water use was only similar during the R4 through R5 growth interval in 2009. Maize water use was 15% lower in KB than the control during the R5 through R6 growth interval, although similar whole-plant water use rates were measured. During the entire reproductive period, maize in the control averaged 0.45 cm $d^{-1}$ compared with 0.39 cm $d^{-1}$ in KB. This response could have been exacerbated in the control if air temperatures in July were not considerably below normal because July rainfall was 37% below normal. These results combined with 8% greater dry grain mass indicate the maize in the KB treatment utilized resources more efficiently than maize growing in the control. The HI data for KB and the control also support this conclusion (0.50 vs. 0.47). Reproductive water use efficiency was 14% higher in KB than the control in 2009.

**Table 7. Maize reproductive water use efficiency (RWUE) for the control without a living mulch and maize growing in a Kentucky bluegrass living mulch between silking (R1) and physiological maturity (R6) in 2008, 2009, and 2010 near Ames, IA.**

| Treatment | Dry grain mass | Water use R1 to R6 | RWUE |
|---|---|---|---|
| | g $m^{-2}$ | cm $m^{-2}$ | g grain $cm^{-1}$ water |
| | | 2008 | |
| Control | 1113 | 26.2 | 42 |
| Kentucky bluegrass | 788 | 15.5 | 51 |
| | | 2009 | |
| Control | 1011 | 27.4 | 37 |
| Kentucky bluegrass | 1087 | 26.0 | 42 |
| | | 2010 | |
| Control | 1068 | 21.1 | 51 |
| Kentucky bluegrass | 772 | 18.8 | 41 |

The 2010 growing season was similar to the 2008 season in terms of excessive rainfall, although the timing was shifted toward later in the season. Above-normal air temperatures in August combined with 330% above-normal rainfall greatly accelerated the grain-filling period. In a 49 d reproductive phase, maize in the control and KB used 21.1 and 18.8 cm of water and averaged 0.44 and 0.38 cm water $d^{-1}$. Similar LAI was measured at all sampling periods in 2010 between the control and KB and were 2.62 in the control and 2.47 in KB at the R3 growth stage. Water use was similar at the R1 through R2 growth interval in 2010. Otherwise, maize in the control used greater water than KB during the remaining growth intervals except during the R3 through R4. Dry grain mass was significantly lower in the KB treatment in 2010 and this resulted in 24% greater RWUE in the control than KB. Kernel number again contributed to the large grain yield reduction in

2010, with the KB treatment producing 23% fewer kernels per square meter than the control. Similarly to 2008, maize productivity in the KB strip-till treatment was superior to the no-till comparison. Maize grain dry mass in the strip-till treatment averaged 1003 g $m^{-2}$ with an HI of 0.54 compared with 0.52 in the control. Maize RWUE in this treatment would range between 48 and 53 g grain $cm^{-1}$ water, assuming whole-plant water use ranged between 18.8 and 21.1 cm. In spite of the potential for CF to retain water in the soil profile, CF also exhibited the greatest negative effect on grain yield during the 3-yr study. Only in 2009 did CF produce competitive yields among these treatments, with significant reductions measured in 2008 and 2010.

Averaged across all years, maize water use rates during reproductive growth in the control exhibited a bimodal response. Average water use during the five growth intervals (R1–R2, R2–R3, R3–R4, R4–R5, and R5–R6) was 0.58, 0.46, 0.51, 0.37, and 0.26 cm $d^{-1}$. A negative linear response was observed in the LM treatment. Averaged across all years, water use rates were 0.47, 0.41, 0.37, 0.26, and 0.22 cm $d^{-1}$. Averaged across years, the largest decline in the rate of water use occurred between R3 through R4 and R4 through R5 (0.11 cm $d^{-1}$) in KB and the control (0.14 cm $d^{-1}$). These rates are well above those reported for maize by Zeggaf et al. (2008) who measured whole-plant transpiration between 56 and 67 d after emergence (DAE) using a similar technique. Assuming a 14-h measurement period, the average transpiration rate they measured was 0.31 cm $d^{-1}$, although the plant population in their study was unusually low (4 plants $m^{-2}$) and the reported LAI was also surprisingly low for maize at 67 DAE (1.3). In the present study, maize in the control treatment was silking at 66, 64, and 54 DAE in 2008, 2009, and 2010 with an LAI of 2.38, 4.42, and 3.59.

## CONCLUSIONS

Maize yield in a KB LM treatment was not decreased because of soil water deficits during the 3-yr study. In contrast, the LM treatments increased SWC in two of three wet years and likely lowered maize yield because of excessive SWC. Maize RWUE was higher in the KB treatment than the control in 2 of 3 yr, although in one of these years the higher efficiency was achieved at the expense of overall productivity. Maize water use exhibited a bimodal response during reproductive growth in the control compared with a simple negative linear relationship in KB. Additional research under varying management and climatic conditions will further quantify the risk of LM production systems on water usage and resource competition when growing continuous maize with stover removal.


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Mention of trade names or commercial products is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.


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